Pathways to Reducing Jitter in Q-Switched and Cavity-Dumped 2 μm Lasers

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Abstract: Q-switched and cavity-dumped 2 μm lasers suffer from fluctuations in build-up time and other parameters on a pulse-to-pulse basis. This jitter has been characterised and will be presented along with progress made towards its reduction.

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1. Motivation

Lasers operating in the wavelength region around 2 μm are of interest for applications including spectroscopy, remote sensing and microsurgery, as well as for pumping optical parametric oscillators (OPOs) and solid-state lasers operating further in the mid-infrared [1, 2]. Pumping non-linear optical systems, such as OPOs, requires high intensities; this could be achieved using the well-established Q-switching technique to generate pulses with high peak powers and pulse energies. Such systems also find applications in laser ranging and machining [3].

The standard Q-switching technique is often not ideal for applications requiring fixed pulse duration as this is determined by the gain dynamics, which are hard to control. Q-switched cavity dumping [4] is a variation on the standard Q-switching technique that uses the switchable loss as a switchable output coupler (as opposed to the fixed output coupling used in standard Q-switching). Using this technique, the pulse duration becomes decoupled from the gain dynamics in the laser medium and dependent only on the cavity round-trip time [5]. The method proceeds as follows: the cavity is held in a high loss state while a large population inversion is built up, then the cavity is switched to low loss and a pulse develops but is kept in the cavity, finally the losses are switched back to high and the cavity field is extracted within approximately one round trip.

Development of a Q-switched cavity-dumped 2 μm laser revealed that while the pulse duration was constant, the peak power of the output pulses varied on a pulse-to-pulse basis. This was attributed to fluctuations in the build-up time of the intra-cavity field leading to variations in the field's amplitude at the fixed time of the cavity dump and hence variations in the amplitude of the cavity-dumped pulse. These fluctuations are collectively called jitter. The build-up time fluctuations are the same in both regimes and so the focus of this research is on analysing and reducing jitter in Q-switched lasers. Any improvements will be readily transferred to the Q-switched cavity-dumped case.

Jitter is not routinely discussed in literature on Q-switched lasers but was found by the authors to be a significant problem in Q-switched thulium lasers. This is attributed to the low gain associated with the quasi-three-level nature of thulium; the stimulated emission cross-section is small ($5.0 \times 10^{-21}\,\mathrm{cm}^{-2}$ in Tm:YAP [6] compared to $3.3 \times 10^{-19}\,\mathrm{cm}^{-2}$ for Nd:YAG [7]) and furthermore it suffers from reabsorption of the laser wavelength [6]. The low gain has the effect of increasing the difficulty of achieving high over-pumping ratios (a measure of how far above threshold the laser is before the pulse). Operating at a low over-pumping ratio leads to the build-up time, pulse duration (in the Q-switching case), peak power and pulse energy being more sensitive to slight variations in the over-pumping ratio, due to changes in either the pumping process or losses. This is illustrated in Figure 1 which shows the dependence on over-pumping ratio of the build-up time and pulse duration derived from the rate equations in [8].

2. Characterisation

To study jitter and investigate ways of overcoming it, an electro-optically Q-switched Tm:YAP laser was constructed. The crystal used was a 4 mm × 4 mm × 3 mm, a-cut (Pnma) 4 at.% Tm:YAP, emitting at 1940 nm when pumped at 795 nm. Pumping at this wavelength takes advantage of the cross-relaxation in thulium [6].

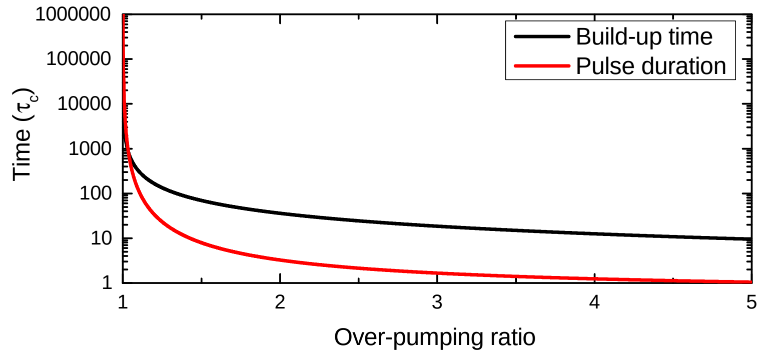

Fig. 1. Theoretical dependence of the build-up time (black) and pulse duration (red) on the over-pumping ratio. Time is in units of the cavity lifetime. The Tm:YAP laser described in Section 2 was operated at over-pumping ratios up to around 3.

In order to obtain detailed knowledge of the laser and due to the lack of data in the literature, a comprehensive data set was taken to analyse the jitter. This data will also serve as a benchmark to quantify any improvements made to the system.

For several pump powers, repetition rates and output couplers, up to 2500 consecutive pulses were recorded. In cases with long build-up times, available memory limited the number of recorded pulses to around 800. It should be noted that repetition rate refers to the Q-switching as the laser is operated with continuous pumping.

The recorded waveforms were analysed to calculate the build-up time, pulse duration, peak power and pulse energy of each pulse. Once these values were known (for a given pump power, repetition rate and output coupling), the mean and standard deviation were calculated for each parameter and histograms showing the distributions were produced. The standard deviation of each distribution was taken to be the magnitude of the jitter. The build-up time, pulse duration, peak power and pulse energy were also plotted against pulse number to see if there were any patterns in the laser behaviour indicating a relation between the build-up of consecutive pulses.

Figure 2 shows the jitter in the build-up time and pulse duration as a percentage of the mean value for each repetition rate with the 5% output coupler. It should be noted that the best case of 1% jitter in the build-up time corresponds to around 5 ns which is approximately 10% of the pulse duration. The jitter is significantly worse at lower pump powers and/or higher repetition rates. This is problematic for stable cavity dumping as explained in Section 1. At the lower repetition rates (50 Hz to 250 Hz in Figure 2), when the time between pulses is greater than or approximately equal to the upper laser level lifetime (4.4 ms [9]), the jitter is fairly insensitive to repetition rate. This is because, after several upper state lifetimes, pumping makes little difference to the population inversion. Performance at higher repetition rates is around an order of magnitude worse. Furthermore, particularly at 5000 Hz, the laser misses some pulses as the pumping process cannot create a large enough population inversion before the switch for a pulse to develop.

Increasing pump power was observed to reduce the jitter in all parameters for each output coupler and repetition rate combination until thermal effects began to degrade performance. The jitter is reduced because at a higher over-pumping ratio (attained through increased pump power), the build-up time and pulse duration are less sensitive to small variations in the over-pumping ratio, which could be due to changes in either the pump process or cavity losses.

The first conclusion drawn from this data set is that jitter becomes more severe at higher repetition rates; especially above 1 kHz where significant efforts to stabilise the laser will be needed if practical systems are to operate at such repetition rates. Secondly, no obvious patterns (beyond the effects of repetition rate and pump power) were found in the data to date.

3. Improvements

Following the completion of the benchmark data set, a number of potential improvements were identified. First, it is known that the over-pumping ratio will vary if the cavity losses fluctuate due to, for example, a vibration disturbing the components. This could be addressed by reducing the number of degrees of freedom in the cavity opto-mechanics.

Second, the laser wavelength is strongly absorbed by atmospheric water vapour [10]. This absorption will degrade performance overall but also local and transient humidity variations in the cavity could affect the jitter. As such, removing moisture from the cavity is a priority.

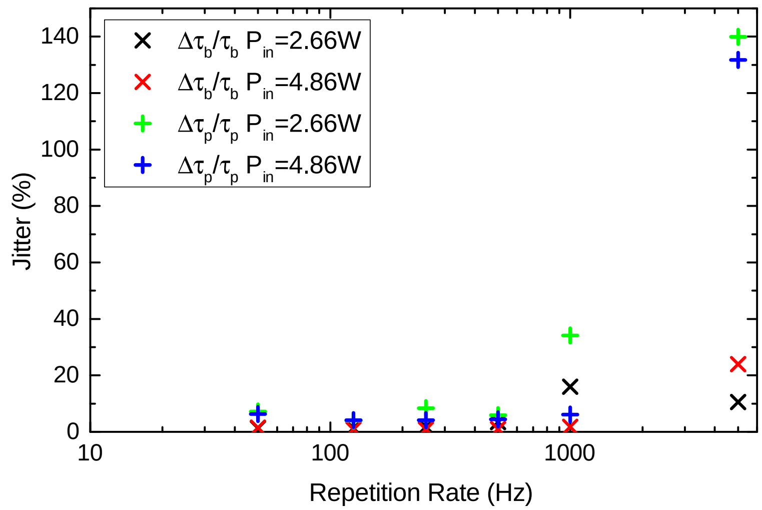

Fig. 2. Percentage jitter in build-up time ($\Delta\tau_b/\tau_b$) and pulse duration ($\Delta\tau_p/\tau_p$) for the 6 repetition rates with 5% output coupling. Data is shown for two incident pump powers to show the effect of increasing pump power on the jitter. In general, a higher pump power reduced the jitter.

Thirdly, any pulse-to-pulse variations in the spectral mode content could contribute to the jitter [11]. This could be addressed by limiting the number of modes on which the laser can operate.

In summary, the jitter in a Q-switched laser has been identified and measured over a range of operating parameters. Work is ongoing to reduce the jitter in the system. The results of inserting etalons into the cavity to reduce the linewidth will be presented and the effect on the jitter will be discussed. Also, the success of a ruggedised system and the dessication of the cavity will be explored.

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